Benefits and Risks of TRANSGENIC,

A transgenic clone of hybrid poplar (*Populus tremula x alba*) shows evidence of resistance to Roundup® treatment in a greenhouse trial (K.-H. Han, C. Ma, L. Jouanin, G. Pillate, and S. Strauss, unpublished data).The genes transferred include one that degrades glyphosate in cells and another that encodes a modified target enzyme to which glyphosate binds only weakly (Padgette et al. 1996). Both trees were saturated with a 0.5 percent solution of Roundup®.

By Steven H. Strauss, Steven A. Knowe, and Jeffery Jenkins

Genetically engineered plants are making their way into food and fiber production. Since 1987 there have been more than 2,300 field trials of transgenic crops at more than 9,400 locations in the United States. Crops engineered for herbicide resistance have been field tested more than any other class of transgenic crop (Beck and Ulrich 1993; Goy and Duesing 1996), and several herbicide resistant varieties have recently been deregulated by the US Department of Agriculture (Schechtman 1996). Plantings of Roundup Ready® soybeans, canola, maize, and cotton are expected to cover more than five million hectares in 1997 (D. Duncan, Monsanto, pers. commun.).

Many plants exhibit natural variability in their responses to herbicides because of physiological or morphological features; this variability is the basis for herbicide selectivity. Tolerance to glyphosate in Populus, for example, depends both on the clone and on seasonal timing of application (Netzer and Hansen 1992). Resistance, on the other hand, is a site-of-action mechanism that prevents an herbicide from producing a toxic effect in the plant (Holt 1992). The molecular basis for resistance is one of three biochemical mechanisms: (1) herbicide detoxification, (2) target enzyme insensitivity because of changes in chemical affinity for the herbicide or overexpression of the target, or (3) lack of herbicide uptake and translocation. Genetic engineering has been used to introduce genes whose products detoxify herbicides and reduce target enzyme sensitivity (reviewed in Dekker and Duke 1995). It can impart very high levels of specific resistance without appreciable effects on other agronomic characteristics.

Genetic engineering of herbicide resistance has been singled out by some groups as a misuse of biotechnology (Goldburg 1992) because it assumes continued reliance on synthetic chemicals, which are viewed as incompatible with sustainable agriculture and likely to promote the creation and spread of herbicide-resistant weeds. In addition, there have been professional challenges to high-input models of agriculture that rely heavily on energy and chemicals

ROUNDUP READY® Cottonwoods

Competition from weeds compromises the survival and growth of hybrid cottonwoods. These trees in western Oregon were all planted at the same time and were in their fourth growing season. in the foreground, weeds were not controlled after tree planting; trees consequently suffered very poor growth and high mortality because of weed competition and girdling by voles. (W. **Schuette, James River, pers. commun.).**

(Radosevich and Ghersa 1992). Opposition to herbicides led by special interest groups has resulted in their ban on several publicly owned forests in the United States and Canada (Wagner 1993).

Intensive culture, however, can release marginal and wild lands from pressure for farm and fiber production, and conversion of agricultural land to perennial fiber crops can reduce soil erosion and chemical inputs (Ranney and Mann 1994). Rather than increase use of herbicides, engineered herbicide resistance might actually reduce total application of herbicides and favor those herbicides with superior environmental attributes (e.g., Giaquinta 1992; Hoyle 1993; Padgette et al. 1996). The benefits of herbicides to the economy (Zilberman et al. 1991) are predicted to increase as a result of herbicide-resistant crops (Wheat and Hedberg 1993).

We believe that there is no simple answer as to whether high-intensity systems and the use of herbicides and genetic engineering to improve their efficiency are inherently good or bad. Resolution will be case specific and will require attention to the diverse characteristics of particular herbicides, crop species, cropping systems, and production alternatives. This viewpoint is supported by the large differences in the toxicity and environmental behavior of herbicides, some of which appear to be less toxic than commonly ingested foods and medicines (Walstad and Dost 1984).

At Oregon State University, the Tree Genetic Engineering Research Cooperative- a consortium that includes Alberta Pacific, Boise Cascade, US Department of Energy, Electric Power Research Institute, Georgia Pacific, International Paper, James River, MacMillan Bloedel, Potlatch, Shell, Union Camp, Westvaco, and Weyerhaeuser is studying means for genetic modification of hybrid cottonwood trees. The clones of interest are mostly hybrids between eastern cottonwood (*Populus deltoides*) and black cottonwood *(P trichocarpa*), although other poplar species are also used as parents. These trees are primarily being grown on agricultural lands under rotations as short as six years. We undertook a pilot analysis of how vegetation management practices are likely to change with the use of cottonwoods engineered for resistance to glyphosate, which is the active ingredient in Roundup®, Accord®, and Rodeo® herbicides.

Pros and Cons

Risks. The primary risks associated with herbicide-resistant crops are increased use of herbicides and accelerated selection of herbicide-resistant weeds (Goldburg 1992). When herbicide-resistant crops become widely available, more land may be treated with herbicides (Giaquinta 1992). The availability of herbicide-resistant crops may also tempt farmers to misuse her bicides and abandon nonchemical weed management practices, possibly aggravating surface- and groundwater contamination (Burnside 1992; Giaquinta 1992; Goldburg 1992).

Two serious risks of deploying herbicide-resistant crops are the potential for selection of herbicide-resistant weed populations and the transfer of resistance genes to interfertile weeds when engineered crops outcross (Burnside 1992; Radosevich et al. 1992; Mikkelsen et al. 1996). Repeated use of single herbicides can cause a shift of species composition toward *species* most tolerant of the herbicide, necessitating management tactics to prevent their buildup (e.g., by use of tillage and alternative herbicides).

Of more concern, however, are evolutionary changes caused by herbicide application that lead to development of resistance within species. Over the past 20 years, repeated use of the same classes of herbicides has resulted in selection of resistant biotypes (Holt 1992). Holt and LeBaron (1990) cataloged more than 100 cases of natural resistance to most of the major herbicide families. The resistant biotypes appear to arise from small, preexisting populations that increase when selection pressure from herbicides is repeatedly applied.

Many crop species grow in proximity to weedy relatives with which they are either highly interfertile or to which they can transmit genes through bridge species or the formation of semisterile hybrids (Snow and Palma 1997). Examples in North America include the mustards, sunflowers, squashes, and most forest trees. In these cases, the widespread planting of herbicide-resistant crops could facilitate concomitant development of resistance in weeds (e.g., Mikkelsen et al. 1996). For forest tree species, which have undergone very little domestication, the weedy relatives are very similar to the crop species themselves; barriers to gene escape are therefore very low (Strauss et al. 1995).

Benefits. The main advantage of herbicide-resistant crops is that growers can select herbicides on the basis of cost, environmental safety, and toxicity to weeds-not *nontoxicity to* the crop. In their absence, managers often apply more costly, less effective, narrowerspectrum, and environmentally less desirable herbicides (Dekker and Duke 1995), and multiple applications of several kinds of herbicides are usually necessary to control weeds.

Use of resistant crops would reduce the need for "insurance" preemergence treatments; some herbicides could be avoided until a problem developed, reducing the number, and therefore the cost, of herbicide treatments (Burnside 1992). Giaquinta (1992) pointed out that even though the total area treated with herbicides may increase when resistant crops are used, the total amount of chemical applied may decline because application rates for the newer classes of herbicides are often much lower (grams instead of kilograms per hectare). At least some of these benefits seem to apply to engineered glyphosate resistance. An analysis of herbicide applications to soybeans in the United States showed that use of glyphosate resistant soybeans may allow farmers to reduce total herbicide use by as much as one-third (Diane Re, Monsanto, pers. commun.).

The use of herbicide-resistant crops would provide more options for integrated vegetation management. Growers could take advantage of autecological characteristics of weeds and crops, such as habitat requirements, modes of reproduction, growth habit, phenology, and response to disturbance (Wagner and Zasada 1991). For example, herbicide applications could be timed to coincide with emergence or shootflushing of weeds, times when nonresistant crops themselves are usually highly sensitive. Safe and effective postemergence treatments could be useful for managing recalcitrant weeds (Burnside 1992; Giaquinta 1992), which may require high rates of application that could be tolerated only by highly resistant crops.

More effective weed control may reduce the number of times agricultural fields need to be cultivated or allow notill systems to be used. This could markedly reduce soil loss in erosion prone areas, thus conserving soil fertility and reducing nonpoint-source pollution (Pimentel et al. 1995). More effective weed control should also reduce the demand for irrigation and fertilization-which can be major operating costs and environmental concerns.

Cottonwood Silviculture

In recent years, several large plantations of hybrid cottonwoods have been established both west and east of the Cascades in Oregon and Washington. About 33,000 hectares of hybrid cottonwoods are currently planted in the Northwest. Operational harvesting in western Oregon and Washington by James River Corporation began in 1991 (about 400 hectares annually). West of the Cascades, MacMillan Bloedel, Georgia Pacific, and a number of farmers have also begun plantation programs. In eastern Oregon and Washington, Potlatch and Boise Cascade are farming cottonwoods on former agricultural lands under drip irrigation systems that supply water, fertilizers, and some pesticides.

Nationally, hybrid poplar plantations are also increasing and could expand greatly if the trees are adopted as a bioenergy crop. There were approximately 12,000 hectares of poplar plantations in the southeastern and north-central United States in 1995, and these areas may double by the turn of the century. The potential area suitable for bioenergy crops in the nation has been estimated at 25 million to 50 million hectares, a significant portion of which would likely be planted with poplars (Hohenstein and Wright 1994; G. Tuskan, Oak Ridge National Laboratory, pers. commun.).

Clones used in production are selected on the basis of growth-and-yield, disease resistance, and environmental adaptation. Typically, unrooted dormant cuttings are planted in rows 3 meters apart at a 2- to 2.5-meter spacing. Trees are harvested after six to eight years, when 25 to 33 meters tall. During the first growing season after planting, nearly total weed control is desired to ensure survival of the cot

Herbicide Toxicology

Glyphosate-based herbicides are widely known for their relatively benign environmental characteristics, and the use of glyphosate-resistant trees assumes that continued or expanded use of glyphosate is desirable or at least acceptable. We therefore briefly review the basic concepts of environmental toxicology and summarize glyphosate's toxicological characteristics based on its registration with the Environmental Protection Agency (EPA).

Fate of pesticides in the environment. The potential impact of a pesticide on human health and the environment is determined by its pattern of use, environmental fate, and toxicity. For noncarcinogenic pesticides, inherent toxicity is determined by dose; for carcinogenic pesticides, toxicity is estimated as a dose-related probability of cancer. The pesticide's environmental fate (Neely 1994), characterized by initial distribution, persistence, and mobility, affects the potential for exposure and therefore determines dose.

Initial distribution of a pesticide in the environment is determined by the formulation, method, and rate of application, as well as geographic and climatic factors. Persistence is the time required for the pesticide to degrade to "nontoxic" products by microbial, chemical, or photochemical pathways. Degradation rates are greatly influenced by environmental factors. The active ingredient in a pesticide should degrade slowly enough to be efficacious yet fast enough to minimize its potential for adverse effects on humans and other nontarget organisms.

Pesticide mobility may cause redistribution within the application site or movement of some amount of pesticide off-site. Mobility is determined by a pesticide's water solubility, lipid solubility, and vapor pressure, as well as adsorption to soil, vegetation, and other surfaces. Highly water-soluble pesticides that are not strongly absorbed are likely to be redistributed by runoff or leaching, and lipid soluble pesticides have a high likelihood of bioaccumulation (Connolly and Thomann I 992). Water-soluble pesticides, including glyphosate, require a wetting agent (surfactant) for adequate penetration of the plant surface (Buckovac I 976). Pesticides may also be lost by volatilization from soil and leaves into the atmosphere.

By law, all active ingredients, formulations, and uses of pesticides must be tested for potential adverse effects on human health and the environment. Testing standards are updated and new tests are required as our knowledge increases. Consequently, most pesticides must be reregistered to meet current testing requirements. When the requirements have been met to the satisfaction of the EPA, the agency issues a Registration Eligibility Decision summarizing its risk assessment and identifying any outstanding generic and product-specific data requirements.

Environmental characteristics of glyphosate. The EPA's assessment for the isopropylamine and sodium salts of glyphosate indicates that glyphosate is of low oral and dermal acute toxicity to humans. For comparative purposes, EPA categorizes pesticides by their short-term toxicity on a scale of I (most toxic) to IV (least toxic). Most undiluted glyphosate formulations are toxicity category III (EPA 1 993). Glyphosate is not mutagenic or teratogenic and has been classified as a group E carcinogen, with no evidence of carcinogenicity for humans. Plant uptake from soil of glyphosate and its major metabolite, aminomethyl phosphoric acid, is limited; EPA's worst-case risk assessment of glyphosate's many registered uses for food production concludes that human dietary exposure and risk are minimal. Because of glyphosate's low acute toxicity, exposure generally is not expected to pose undue risks to workers and other applicators.

Glyphosate adsorbs strongly to soil and is not expected to move below the 6-inch soil layer; residues are expected to be immobile. The herbicide base is readily degraded by soil microbes to aminomethyl phosphoric acid, which is then degraded to carbon dioxide. Glyphosate is therefore not likely to reach groundwater, but it does have the potential to reach surface water through erosion as it adsorbs to soil particles suspended in runoff. It is slightly toxic to practically nontoxic to aquatic invertebrates, honeybees, and fish and is no more than slightly toxic to birds. Given current data, the agency has determined that the effects of glyphosate on invertebrates, fish, birds, and mammals are minimal. Additional terrestrial plant studies are required to assess potential risks to nontarget plants.

Because of its water solubility, glyphosate is formulated with a surfactant in Roundup Pro^{Tm} and Roundup Ultra ™ products. Surfactants aid in leaf wetting and herbicide penetration into the plant surface, but they are also responsible for irritating the skin, eyes, and mucous membranes after acute exposure. The surfactant used in current formulations is a neutralized ethoxylated tallow amine. The acute mammalian toxicity potential of these formulations has been assessed in a number of studies (M. McKee, Monsanto, pers. commun.) submitted to the EPA after the agency's risk assessment was published. The results show acute oral, dermal, or inhalation exposure to be practically nontoxic, although slightly irritating to skin and moderately irritating to eyes. They do not cause allergic skin reactions.

Based on those results, Roundup Ultra ™ is placed in acute toxicity category III, requiring a caution signal; ecotoxicology studies show it to be practically nontoxic to birds and, when it enters aquatic systems, moderately toxic to fish and aquatic invertebrates (M. McKee, Monsanto, pers. commun.).

tonwood cuttings and to produce optimum growth. Without vegetation control, survival may be reduced by 25 to 50 percent (Schuette 1990) and growth by at least 50 percent (Schuette 1990, 1991). In addition to controlling competition, vegetation management reduces habitat for animals that may damage cottonwoods (R. Fletcher, OSU Extension *Service, pers.* commun.). *Voles* and other rodents girdle cuttings in western Oregon, and coyotes chew drip irrigation lines east of the Cascades. In the Lake States, northeastern United States, and Canada, where poplars are often planted on cutover forestlands, postplanting vegetation control can be extremely difficult, and inadequate control has led to many plantation failures. Intensive vegetation control is gener*ally* considered essential for short-rotation culture of cottonwoods and other poplars throughout North America (Dickmann and Stuart 1983; Hansen and Netzer 1992).

Cottonwood culture on the west side of the Cascades, as in the eastern United States, relies heavily on mechanical site preparation and mechanical cultivation *(table 1).* In addition, glyphosate in a tank mix with a preemergent herbicide (terbacil, diuron, oxyfluorfen, or sulfometuron) is applied in westside plantations. The combination of mechanical cultivation and chemical weed control can double growth over that obtained with cultivation alone (Schuette 1991).

Eastside fiber production uses trifluralin, which must be incorporated into the soil to prevent volatilization and photodegradation in sunlight *(table 1).* Besides trifluralin, 2,4-D is applied before planting in converted alfalfa fields and as a tank mix with glyphosate for postemergence control of broadleaf plants during the dormant season. Glyphosate applied with wick applicators is used during the growing season, and weeds between the rows are mowed. However, weed control with wick applicators is inconsistent, and regrowth of weeds following mowing is rapid. Mechanical cultivation is increasing in eastside cottonwood culture because it is more effective than other methods, but it can damage drip irrigation lines. Vegetation management is used for two to three growing seasons to ensure plantation success *(W Schuette,* James River, pers. commun.).

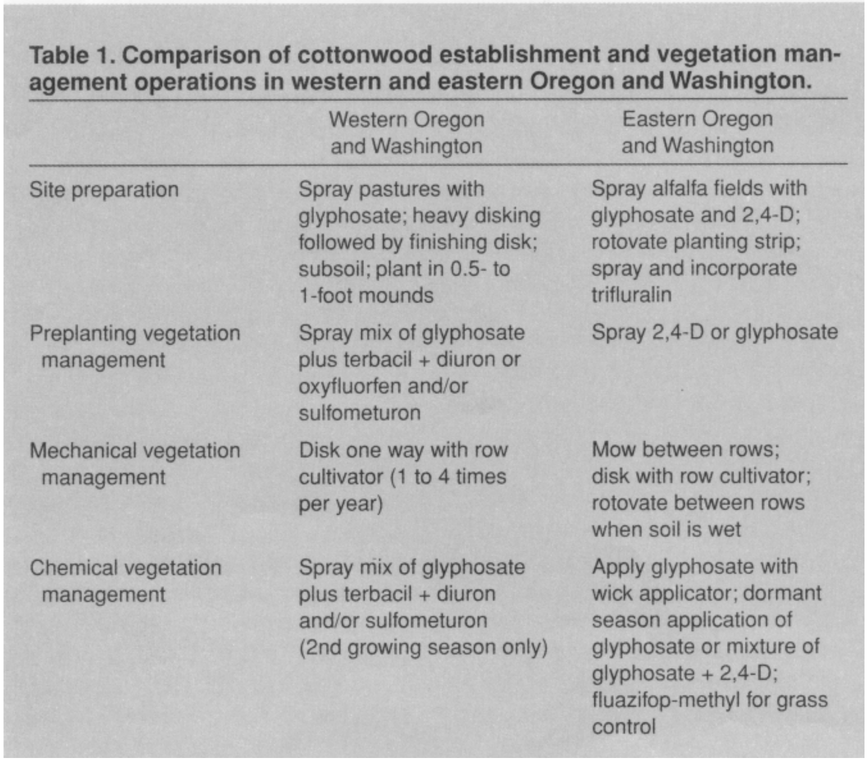

Table 1. Comparison of cottonwood establishment and vegetation management operations in western and eastern Oregon and Washington.

	Western Oregon and Washington	Eastern Oregon and Washington
Site preparation	Spray pastures with glyphosate; heavy disking followed by finishing disk; subsoil; plant in 0.5- to 1-foot mounds	Spray alfalfa fields with glyphosate and 2,4-D; rotovate planting strip; spray and incorporate trifluralin
Preplanting vegetation management	Spray mix of glyphosate plus terbacil + diuron or oxyfluorfen and/or sulfometuron	Spray 2,4-D or glyphosate
Mechanical vegetation management	Disk one way with row cultivator (1 to 4 times per year)	Mow between rows; disk with row cultivator; rotovate between rows when soil is wet
Chemical vegetation management	Spray mix of glyphosate plus terbacil + diuron and/or sulfometuron (2nd growing season only)	Apply glyphosate with wick applicator; dormant season application of glyphosate or mixture of glyphosate + 2,4-D; fluazifop-methyl for grass control

Growing Transgenic Clones

Risks. Although evolution of herbicide-resistant weed populations can be accelerated by intensified use of a single herbicide, this is unlikely with glyphosate use and short-rotation cottonwood production. Herbicide treatments are typically required only for the first two to three years of a minimum six-year rotation, after which the trees' crowns suppress weeds. At the end of the rotation, sites are intensively prepared to control *weeds* and remove stumps; in addition to glyphosate and mechanical methods, other chemicals are typically employed. These practices should eliminate most glyphosate-tolerant plants that may have developed.

To date, despite many years of extensive use worldwide (Padgette et al. 1996; Riemenschneider 1997), there has been only a single report of a glyphosate-tolerant weed population that *developed because of* repeated glyphosate use (Gressel 1996). The rate of resistance development with most other herbicides appears to be much higher (Holt 1992). The difference likely results from glyphosate's low persistence in the environment, the scarcity of degradation pathways in plants, and the biochemical difficulty of creating mutations in the target enzyme that reduce glyphosate binding but do not also impair enzymatic function (Padgette et al. 1996). It therefore appears unlikely that evolution of resistant populations will be significantly accelerated by applications of glyphosate to cottonwood plantations.

Transgenic hybrid poplars can interbreed with wild populations. Cottonwoods typically begin flowering at least two years before the end of even a short rotation (B. Stanton, James River, pers. commun.), and seeds and pollen could carry resistance genes long distances outside plantations. Cottonwoods do not naturally hybridize with any of the aspens or white poplars (section Populus or *Leuce)* (Pryor and Willing 1982; Eckenwalder 1996) but can usually cross with other cottonwood species, including the widespread, northwestern native black cottonwood (section *Tacamahaca),* and many other species and hybrids of sections *Aigeiros* and *Tacamahaca.* Black cottonwoods are widespread along streams in low valleys west of the Cascades near the new cottonwood plantations, and riparian populations east of the Cascades are also likely to be within reach of seed and pollen from irrigated plantations.

Despite the potential for genetic interactions with wild populations, however, transfer of the resistance transgene will often not be of significant concern. Cottonwood regeneration requires a combination of seasonally moist soils, high sunlight, and an absence of competition from herbaceous plants; stand regeneration is therefore rare (DeBell 1990). In Oregon and in arid regions of the West, natural populations of cottonwoods are virtually restricted to riparian and wetland habitats (DeBell 1990). Because glyphosate is rarely used for weed control in these wild environments, trees with resistance to glyphosate should be of little concern and have little selective advantage. Cottonwoods are not common or competitive in upland habitats in Oregon, where conifer management predominates and where weed control might be compromised by the appearance of escaped transgenic trees. Because of aridity in unirrigated drylands and tillage in irrigated or mesic lands, cottonwood is not a significant weed for annually harvested crops.

Cottonwoods may, however, need to be controlled through use of herbicides in drainage ditches, rights-of-way, and perennial agricultural crop fields. In cooler areas-such as in northern Washington, British Columbia, and in the north-central United Statespoplars are less restricted in their distribution and can be significant competitors in some forest stands managed for conifers. In addition to the predominantly riparian black cottonwood, balsam poplar (*Populus balsamifera) is* sexually compatible with hybrid cottonwoods; it thrives in uplands (McLennan and Mamias 1992). Aspens are common throughout Canada and the north-central United States.

Tactics

Should resistant wild trees become a problem, they could be controlled by other vegetation management strategies, including the commonly used herbicides triclopyr (Garlon') and imzapyr (Arsenal"), as well as other herbicides effective on poplars (Peterson and Peterson 1992). Nonetheless, because of the complexity of potential effects, we believe that sexually competent, glyphosate- resistant cottonwoods should not be grown without a case specific analysis (e.g., Timmons et al. 1996) of the frequency, impacts, and mitigation options for resistant trees likely to result from transgenic plantations. Such studies are required by regulatory agencies as part of applications for commercialization of transgenic crops. However, the laxity of some reviews and the low level of federal funds for supporting scientific research on biosafety of transgenic crops have been criticized by some ecologists and environmental groups (Snow and Palma 1997).

To allay concerns over the spread of resistance genes, researchers are studying genetic engineering of male and female sterility. Engineered sterility would prevent infusions of transgenic pollen or seed into wild populations. It also might be critical to safe use of the multiple-herbicide-resistant lines. Because cottonwoods are planted as vegetative propagules, sterile trees would pose no obstacles to deployment, though they could not be used for further breeding unless sterility was designed to be reversible. Cottonwoods can spread vegetatively, but the rate and degree of vegetative dispersal are limited compared with those resulting from seed and pollen; dispersal should be largely restricted to riparian areas, via water transport. Genetically engineered sterility has already been demonstrated in crop plants and is being tested in poplars (Strauss et al. 1995).

In addition to engineered sterility, other genetic tactics may help limit gene escape. The use of intersectional hybrids, such as the *Populus deltoides x trichocarpa* hybrids that are widely grown in the Northwest, may constrain gene movement from plantations because their sexual progeny are likely to have lower fertility and fitness in the wild than native cottonwoods. Triploid hybrid clones of cottonwood are also used commercially; they appear to have high levels of sterility in the laboratory and the field (Bradshaw and Stettler 1993; Strauss et al. 1996).

Introducing resistance genes may pose concerns because of the gene transfer process itself, which is somewhat mutagenic (De Block 1993). In addition, genes used to facilitate identification of transgenic plants have raised some concerns, and the herbicide resistance-imparting genes themselves can sometimes impair physiological processes. Mutations that significantly affect tree growth should be eliminated when engineered lines are screened for normal growth, adequate levels of gene expression, and herbicide resistance in field trials. Most other transgenes used during the gene transfer process, such as the commonly used antibiotic resistance genes, appear to be of little concern in forest systems; the NPTII gene for resistance to Kanamycin, for example, is ubiquitous in natural populations of soil organisms, and its protein product is safe even for human consumption (Fuchs et al. 1993).

Although some kinds of herbicide resistance genes have been shown to seriously disturb host physiology, genetically engineered resistance has been largely free of these effects (Dekker and Duke 1995; Snow and Palma 1997). The first glyphosate resistance genes studied in poplar and other species were not effective at imparting commercial levels of resistance (reviewed in Riemenschneider 1997), but the CP4 gene in current use appears both to provide strong levels of resistance and to have no deleterious effects on growth in soybeans (Delannay et al. 1995; D. Duncan, Monsanto, pers. commun.) or, in the limited testing to date, in poplars (Strauss et al. 1996, unpubl. data).

Advantages

The use of glyphosate- resistant cottonwood clones should provide new opportunities for integrated vegetation management. Glyphosate applications could be scheduled for periods of high weed sensitivity-periods normally avoided because of the sensitivity of the crop. Weed problems that might be alleviated by the use of glyphosate-resistant cottonwoods include those caused by smartweed (*Polygonum persicaria)* in western Oregon, Russian tumbleweed *(Salsola iberica)* in eastern Oregon and Washington, and woody vines that become established late in the first growing season in southeastern cottonwood plantations. Current integrated vegetation management treatments do not control these competitors, and glyphosate cannot be applied during the period of active growth without risking damage to the cottonwoods.

The use of herbicide-resistant cottonwoods may permit more flexibility in the selection and timing of treatments. Reliance on intensive mechanical site preparation and preemergence herbicides, such as trifluralin, terbacil, and diuron, may be reduced if glyphosate-resistant cottonwood clones are available. Mechanical cultivation may be reduced but not likely eliminated.

In the West, the need to control voles with toxic bait might be reduced if weed control were more effective. In eastern Oregon and Washington, wick applications of glyphosate twice a year may be replaced by spraying glyphosate up to three times in the first growing season. This would provide better weed control without risking damage to the cottonwoods and could serve as a backup for preemergence treatments. On the east side, where inconsistent weed control by trifluralin often results in weed "hot spots," spot-spraying with glyphosate would be a useful option (J. Eaton, Potlatch, pers. commun.).

The cultivation of glyphosateresistant cottonwoods could result in more applications of glyphosate, but the use of preemergence, soil-active herbicides chanical site preparation and cultivation permitted by more effective weed control with glyphosate could reduce soil erosion and subsurface compaction (the hardpan known as plowpan) and thus might stimulate tree growth on some sites. Water usage and application of fertilizers, which are large costs in dryland cottonwood production, should be reduced if weed control is more effective.

Research Needs

The risks and benefits of genetically engineered cottonwoods require careful analysis if industries and those with environmental concerns are to be convinced of their utility and safety. One critical need is for studies of the predicted effects of transgene movement on weed control in lands near plantations. Empirical studies of hybrid establishment and fitness, combined with population modeling and geographic information systems, should allow reasonable predictions of the effects of gene movement over the landscape over time (Strauss et al. 1996; Riemenschneider 1997). The short-term, empirical studies of transgene effects proposed for annual crops (Snow and Palma 1997) are not practical for trees.

Also needed is a direct comparison of plantation silviculture with and without genetically engineered trees. Such a study should assess the yield and level of resistance in these trees as well as their economic and environmental benefits. The current methods of site preparation, planting, and vegetation management should be compared with cultural regimes that take advantage of glyphosate resistance by, for example, reducing use of preemergence herbicides, reducing mechanical cultivation, and applying glyphosate during the growing season. Measured variables might include irrigation water, number of cultivations, amount of fertilizer, animal protection measures, production costs, and rates and timing of herbicide applications. Measured responses might include tree growth with and without glyphosate application, nutrient status, weed population density and composition, runoff water and soil quality, and animal damage. These studies would allow managers and regulatory agencies to assess whether the financial costs and benefits, and the environmental risks, warrant the use of glyphosate- resistant cotton woods.

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Steven H. Strauss is professor, Department of Forest Science, Oregon State University, Corvallis 97331-7501, email: strausss@FSL.orst.edu; Steven A. Knowe was associate professor, Department of Forest Science, Oregon State University; Jeffery Jenkins is extension toxicology and chemistry specialist, Oregon State University Cooperative Extension, Corvallis.